

Naval Medical Research Institute

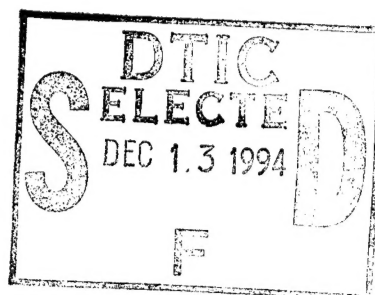
8901 Wisconsin Avenue
Bethesda, MD 20889-5607

NMRI 94-51

July 1994



DENSITY, HEAT CAPACITY, VISCOSITY, AND THERMAL CONDUCTIVITY OF MIXTURES OF CO₂, HE, H₂, H₂O, N₂, AND O₂



L. D. Homer
S. R. Kayar

Naval Medical Research
and Development Command
Bethesda, Maryland 20889-5606

Department of the Navy
Naval Medical Command
Washington, DC 20372-5210

Approved for public release;
distribution is unlimited

19941207 104

NOTICES

The opinions and assertions contained herein are the private ones of the writer and are not to be construed as official or reflecting the views of the naval service at large.

When U. S. Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Please do not request copies of this report from the Naval Medical Research Institute. Additional copies may be purchased from:

National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

Federal Government agencies and their contractors registered with the Defense Technical Information Center should direct requests for copies of this report to:

Defense Technical Information Center
Cameron Station
Alexandria, Virginia 22304-6145

TECHNICAL REVIEW AND APPROVAL

NMRI 94-51

The experiments reported herein were conducted according to the principles set forth in the current edition of the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

This technical report has been reviewed by the NMRI scientific and public affairs staff and is approved for publication. It is releasable to the National Technical Information Service where it will be available to the general public, including foreign nations.

ROBERT G. WALTER
CAPT, DC, USN
Commanding Officer
Naval Medical Research Institute

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.</small>				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE July 1994	3. REPORT TYPE AND DATES COVERED TECHNICAL 10/91 - 07/94		
4. TITLE AND SUBTITLE (U) Density, heat capacity, viscosity, and thermal conductivity of mixtures of CO ₂ , He, H ₂ , H ₂ O, N ₂ , and O ₂ .		5. FUNDING NUMBERS PE - 61153N PR - MR04101 TA - .00D WU - 1103		
6. AUTHOR(S) Homer, L.D. and S.R. Kayar				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Medical Research Institute Commanding Officer 8901 Wisconsin Avenue Bethesda, Maryland 20889-5607		8. PERFORMING ORGANIZATION REPORT NUMBER NMRI 94-51		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Medical Research and Development Command National Naval Medical Center Building 1, Tower 12 8901 Wisconsin Avenue Bethesda, Maryland 20889-5606		10. SPONSORING / MONITORING AGENCY REPORT NUMBER DN241522		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) <p>The thermodynamic properties of gas mixtures are not always well approximated by the average properties of pure gases weighted by the fractional composition. In order to improve our calculations we have turned to the literature to find formulas said to be useful for calculating the properties of mixtures in the range of temperatures and pressures encountered in human diving. Very little has been published on experimental determinations of properties of mixtures, so we have sought principally to verify that the formulas for mixtures give a good match to data on pure gases. In order to match data on pure gases, the values for the critical temperature (TC) and the critical pressure (PC) for H₂ and He were modified. In addition, ad-hoc adjustments have been made to the critical volumes (VC) to make viscosity at low pressures match tables for these two gases. Omega, the acentric factor in the formulas, is taken as zero for all gases. The properties for which we have subroutines are thermal conductivity in watts-meter⁻¹-degree K⁻¹, viscosity in μpoise, density in moles·cm⁻³, heat capacity in Joules·mole⁻¹-degree K⁻¹, and the vapor pressure of water in torr.</p>				
14. SUBJECT TERMS gas physical properties, diving, ventilation, thermoregulation			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	

TABLE OF CONTENTS

	page
ACKNOWLEDGEMENTS	ii
INTRODUCTION	1
THERMAL CONDUCTIVITY	3
VISCOSITY	4
DENSITY	5
HEAT CAPACITY	6
VAPOR PRESSURE OF WATER	7
WHY USE MIXTURE FORMULAS?	7
REFERENCES	10
APPENDIX: Fortran Language Subroutine	12

LIST OF TABLES

TABLE 1: Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot^\circ\text{K}^{-1}$) of pure gases at 300°K	3
TABLE 2: Viscosity (μpoise) of pure gases at 300°K	4
TABLE 3: Density ($\text{mol}\cdot\text{L}^{-1}$) of pure gases at 300°K	5
TABLE 4: Heat capacity at constant pressure ($\text{J}\cdot\text{mol}^{-1}\cdot^\circ\text{K}^{-1}$)	6
TABLE 5: Comparison of mixture formulas (F) with fractional weighting (W), for viscosity (μpoise), and thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot^\circ\text{K}^{-1}$) at 300°K	8
TABLE 6: Comparison of mixtures without water vapor (D) with mixtures with 0.05 atmospheres of water vapor and 0.05 atmospheres of carbon dioxide (W)	9

ACKNOWLEDGEMENTS

We would like to thank Ms. S. Cecire for her conscientious and thorough editorial work.

This work was supported by NMRDC Work Unit No. 61153N MR04101.00D-1103.

The opinions expressed in this paper are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the U. S. Government.

Accession For

NTIS CRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>

Justification

Ext

Distribution

Aviation College

Ext

Aviation for

Ext

A-1

INTRODUCTION

The thermodynamic properties of gas mixtures are not always well approximated by the average properties of pure gases weighted by the fractional composition. In order to improve our calculations we have turned to a book by Reid, Prausnitz, and Poling (1987). This book provides formulas said to be useful for calculating the properties of mixtures in the range of temperatures and pressures encountered in human diving. Very little has been published on experimental determinations of properties of mixtures, so we have sought principally to verify that the formulas in question give a good match to data on pure gases and have trusted to the formulas for the interpolations for mixtures. In order to match data on pure gases, the values for the critical temperature (TC) and the critical pressure (PC) for H₂ and He were changed as suggested by Gunn, Chueh, and Prausnitz (1966). In addition, ad-hoc adjustments have been made to the critical volumes (VC) to make viscosity at low pressures match published values for these two gases. At the suggestion of one of the authors of the book (Poling), omega, the acentric factor in the formulas, is taken as zero for all gases. The properties for which we have subroutines are thermal conductivity in watts·meter⁻¹·°K⁻¹, viscosity in μpoise, density in moles·cm⁻³, heat capacity in Joules·mole⁻¹·°K⁻¹, and the vapor pressure of water in torr.

Thermodynamic properties of pure gases are shown in Tables 1-4 at 300 °K. Pressure is given in bars rather than atmospheres, because the reference sources most commonly report in bars (1 bar = 1.01325 atmospheres). References cited are as follows: a) Weast, R.C., CRC Handbook of Chemistry, 49th edition, Chemical Rubber Co., Cleveland, OH, 1968; b) McCarty, R.D. et al., Selected Properties of Hydrogen (Engineering Design Data,

National Bureau of Standards Monograph 168, U.S. Department of Commerce, Washington, DC, 1981; c) Lide, D.R. (editor), CRC Handbook of Chemistry and Physics, 73rd edition, CRC Press, 1992; d) McCarty, R.D., Thermophysical Properties of Helium-4 from 2 to 1500 °K with Pressures to 1000 Atmospheres, National Bureau of Standards Technical Note 36, U.S Department of Commerce, Washington, DC, 1972; e) Chung, T.-H., et al., "Applications of kinetic gas theories and multiparameter correlation for prediction of dilute gas viscosity and thermal conductivity," Industrial and Engineering Chemistry Fundamentals, Vol. 23, 1984; f) Lange, N.A. (editor), Handbook of Chemistry, Handbook Publishers, Inc., Sandusky, OH, 1946.

THERMAL CONDUCTIVITY

*REAL*8 FUNCTION TK(Y,TIN,PIN)*

Inputs to the function are the vector of mol fractions of CO₂, H₂, H₂O, He, N₂, O₂ in the gas mixture (Y), temperature (TIN, °C), and pressure (PIN, atmospheres). Output is the mixture thermal conductivity (TK, W·m⁻¹·°K⁻¹). Formulas are from Reid, Prausnitz, and Poling, Chapter 10, "Thermal Conductivity" (1987).

TABLE 1
Thermal conductivities(W·m⁻¹·°K⁻¹) of pure gases at 300°K.

GAS	Pressure Bars	Program	Reference
CO ₂	1	0.01724	0.0187,c 0.0166,a
H ₂	1	0.1821	0.1869,c 0.1869,a 0.187,b
	10	0.1822	0.1872,b
	100	0.1926	0.1899,b
H ₂ O	1	0.02121	0.0178,a 0.0181,a
He	1	0.1556	0.1567,c 0.1499,a 0.1474,a 0.155,d
	10	0.1557	0.155,d
	100	0.1624	0.160,d
N ₂	1	0.02646	0.026,c,a
	10	0.02652	0.0263,c
	100	0.03093	0.0319,c
O ₂	1	0.02674	0.0263,c
	10	0.02678	0.0263,c
	100	0.03043	0.0316,c

VISCOSITY

*REAL*8 FUNCTION VISC(Y,TIN,PIN)*

Inputs to the function are the vector of mol fractions of CO₂, H₂, H₂O, He, N₂, O₂ in the gas mixture (Y), temperature (TIN, °C), and pressure (PIN, atmospheres). Output is the mixture viscosity (VISC, μ poise). Formula from Chapter 9, "Viscosity", and from constants in Appendix A of Reid, Prausnitz, and Poling (1987).

TABLE 2
Viscosity in μ poise of pure gases at 300°K.

GAS	Pressure Bars	Program	Reference
CO ₂	1	158.7	151-219,e 152,a
H ₂	1	88.6	89.53,b 89.2,a
	10	88.81	90.7,b
	100	91.83	91.7,b
H ₂ O	1	95.7	100,f
He	1	199.6	199.,d 197.,a
	10	199.9	200.,d
	100	203.3	203.,d
N ₂	1	179.4	180,c 178.1,a
	10	180.3	181,c
	100	204.5	201,c
O ₂	1	207.	206,c 208,a
	10	207.8	207,c
	100	232.2	229,c

DENSITY

*REAL*8 FUNCTION RHO(Y,TIN,PIN)*

Inputs to the functions are the vector of mol fractions of CO₂, H₂, H₂O, He, N₂, O₂ in the gas mixture (Y), temperature (TIN, °C), and pressure (PIN, atmospheres). The subroutine returns the gas density (RHO, mol·cm⁻³). Formula for virial equations from Reid, Prausnitz, and Poling (1987).

TABLE 3
Density (mol·L⁻¹) of pure gases at 300°K.

GAS	Pressure Bars	Program	Reference
CO ₂	1	0.0403	
H ₂	1	0.0401	0.0401,b
	10	0.398	0.399,b
	100	3.78	3.78,b
H ₂ O	1
He	1	0.0401	0.0406,d
	10	0.399	0.404,d
	100	3.83	3.88,d
N ₂	1	0.0401	0.04,c
	10	0.402	0.402,c
	100	4.07	3.989,c
O ₂	1	0.0407	0.04,c
	10	0.401	0.403,c
	100	4.03	4.205,c

HEAT CAPACITY

*REAL*8 FUNCTION CP(Y,TIN)*

Inputs to the function are the vector of mol fractions of CO₂, H₂, H₂O, He, N₂, O₂ in the gas mixture (Y), temperature (TIN, °C), and pressure (PIN, atmospheres). Output is the mixture isobaric heat capacity (CP, J·mol⁻¹·°K⁻¹). Formula and constants in Appendix A of Reid, Prausnitz, and Poling (1987).

TABLE 4
Heat capacity at constant pressure (J·mol⁻¹·°K⁻¹) and 300°K.

GAS	Pressure Bars	Program	Reference
CO ₂	1	37.25	36.6,f
H ₂	1	28.89	29.9,c
	10	28.89	30.0,c
	100	28.89	30.4,c
H ₂ O	1	33.67	..
He	1	20.8	20.8,c
	10	20.8	20.8,c
	100	20.8	20.8,c
N ₂	1	29.18	29.2,c
	10	29.18	29.6,c
	100	29.18	33.4,c
O ₂	1	29.39	29.4,c
	10	29.39	29.9,c
	100	29.30	29.4,c

VAPOR PRESSURE OF WATER

*REAL*8 FUNCTION VPH2O(T,P)*

Input temperature (T, °C), pressure (P, atmospheres) returns vapor pressure of water (VPH20, torr). Formula is Equation 1 from Appendix A of Reid, Prausnitz, and Poling (1987). Pressure correction is from Glasstone (1946). Verified by comparison with Weast (1968). Maximum error <0.25%

WHY USE MIXTURE FORMULAS?

The question naturally arises: Why not calculate mixture properties from an average of the pure gas properties weighted by the fractional composition of the mixture? The answer: This does not always give the correct value, although sometimes the approximation is reasonable. For example, the fractional weighting for density and heat capacity give the same answer as the formulas to within a few percent, and represent a reasonable alternative. Indeed one could use published programs for pure gas properties of N₂ and O₂ (Younglove, 1982), and probably achieve better accuracy than with the present program over some ranges of pressure for some gases. Values for mixed-gas viscosity and thermal conductivity, however, appear very different when the calculations from mixture formulas are compared to the values obtained by fractional weighting.

TABLE 5
Comparison of mixture formulas (F) with fractional weighting (W), for viscosity (μpoise), and thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot^\circ\text{K}^{-1}$) at 300°K

He	N ₂	O ₂	Atm	Viscosity		Thermal Conductivity	
Fractional Composition				F	W	F	W
0.8	0	0.2	1	259	201.1	0.08382	0.1299
0.8	0	0.2	6	259.2	201.3	0.08383	0.1299
0	0.79	0.21	1	185	185.6	0.0265	0.0265
0	0.79	0.21	6	185.5	185.6	0.0265	0.0265
0	0.96	0.04	10	214.4	200.2	0.1362	0.1505
0	0.2	0.8	1	201.3	201.4	0.0267	0.0267

Major differences appear only where He is present. The largest difference shown is for 80% He and 20% O₂ where about 30% discrepancies occur. Unfortunately, little empirical evidence is available to help us decide which values are in fact most reliable. Mixtures with H₂ also have higher viscosities and lower thermal conductivities predicted by the mixture formulas than by fractional weighting.

Another approximation that may frequently be considered is to ignore the presence of water vapor and CO₂. Differences in heat capacity and density are relatively small.

TABLE 6

Comparison of mixtures without water (D) with mixtures with 0.05 atmospheres of water vapor and 0.05 atmospheres of carbon dioxide (W). Viscosity (μpoise), and thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot^\circ\text{K}^{-1}$) are shown. Temperature is 300°K , pressure 1 atmosphere. Other gases were each reduced by 0.05 atmospheres when water vapor and CO_2 were present.

He	N_2	O_2	Viscosity		Thermal Conductivity	
Fractional Composition			D	W	D	W
0.8	0	0.2	259	252.7	0.08382	0.0683
0	0.79	0.21	185	177.8	0.0265	0.0260
0	0.2	0.8	201	191.8	0.0267	0.0262

The effects of omitting water vapor at 1 atmosphere are modest (less than 15%). At higher pressures, CO_2 and water vapor become smaller fractions of the whole, and corrections become even smaller.

REFERENCES

1. Chung, T.-H., Lee, L. L., and Starling, K.E., "Applications of kinetic gas theories and multiparameter correlation for prediction of dilute gas viscosity and thermal conductivity," Industrial and Engineering Chemistry Fundamentals, Vol. 23, pp. 8-13, 1984.
2. Glasstone, S., Textbook of Physical Chemistry, 2nd edition, D. Van Nostrand Company, Inc., 1946.
3. Gunn, R.D., Chueh, P.L., and Prausnitz, J.M., "Prediction of thermodynamic properties of dense gas mixtures containing one or more of the quantum gases," American Institute of Chemical Engineers Journal, Vol. 12, pp. 937-941, 1966.
4. Lange, N. A. (editor). Handbook of Chemistry, Handbook Publishers, Inc. Sandusky, Ohio, 1946.
5. Lide, D.R. (editor). CRC Handbook of Chemistry and Physics, 73rd edition. CRC Press, 1992.
6. McCarty, R.D., Hord, J., and Roder, H.M., Selected Properties of Hydrogen (Engineering Design Data), National Bureau of Standards Monograph 168, U.S. Department of Commerce, Washington, DC, 1981.

7. McCarty, R.D., Thermophysical Properties of Helium-4 from 2 to 1500 K with Pressures to 1000 Atmospheres, National Bureau of Standards Technical Note 36, U.S. Department of Commerce, Washington, D.C., 1972.
8. Reid, R.C., Prausnitz, J.M., and Poling, B.E., The Properties of Gases and Liquids, 4th edition, McGraw-Hill Publishers, 1987.
9. Younglove, B.A., Interactive Fortran Program to Calculate Thermophysical Properties of Six Fluids. National Bureau of Standards Technical Note 1048, U.S. Department of Commerce, Washington, DC, 1982.
10. Weast, R.C., CRC Handbook of Chemistry and Physics, 49th edition, Chemical Rubber Co., Cleveland, Ohio, 1968.

APPENDIX: FORTRAN LANGUAGE SUBROUTINE

G2CON.FOR .. include file for the gas subroutines in G2.FOR

C..

IMPLICIT REAL*8(A-H,M,O-Z)

PARAMETER(NGAS=6)

DIMENSION Y(NGAS),VC(NGAS),TC(NGAS),MW(NGAS),OMEGA(NGAS),PC(NGAS)

C.. DATA PARAMETER/CO2,H2,H2O,He,N2,O2/99-75-77-48-56-59

DATA VC/93.9D0,64.3D0,57.1D0,57.4D0,89.8D0,73.4D0/

C DATA TC/304.1D0,33.D0,647.3D0,5.19D0,126.2D0,154.6D0/

C DATA PC/73.8D0,12.9D0,221.2D0,2.27D0,33.9D0,50.4D0/

C..H2/He changed Gunn etal AICHE J 12,937(1966)

DATA TC/304.1D0,42.D0,647.3D0,10.3D0,126.2D0,154.6D0/

DATA PC/73.8D0,18.8D0,221.2D0,5.8D0,33.9D0,50.4D0/

C..

DATA MW/44.01D0,2.016D0,18.015,4.003D0,28.013D0,31.999D0/

C DATA OMEGA/.239D0,-.216D0,.344D0,-.365D0,.039,.025/

DATA OMEGA/6*0./

DATA R/8.3144/

C..

G2.FOR subroutines for calculating mixed gas thermal properties

C..

REAL*8 FUNCTION TK(Y,TIN,PIN)

C..

C.. Input is the vector of mol fractions of CO2,H2,H2O,He,N2,O2 in the

C.. gas mixture, Y. Temperature, TIN, degrees C, pressure PIN, atmospheres.

C.. Output is the mixture thermal conductivity in W/(m-K)

C.. Formula from pages 491-576, chapter on thermal conductivity

C.. and mixing formulas 9-5.24 to 9-5.44,10-3.17 and 10-6.1 to 10-6.5

C.. and constants in appendix A of Reid, Robert C, John M Prausnitz,

C.. Bruce E Poling; The properties of gases and liquids, 4th edition

C.. McGraw-Hill NY,NY ,1987.

C..

C.. TC, and PC for H2 and He are changed as suggested by Gunn etal

C.. AIChE J 12,937(1966), in addition ad-hoc adjustments have been made to

C.. VC to make viscosity at low pressures match tables for these 2 gases

C.. omega is taken as zero for all gases

C..

```
INCLUDE 'g2con.for'
```

C..

```
DIMENSION AI(7),B(7)
```

```
DATA AI/2.4166D0,-5.0924E-1,6.6107D0,1.4543D1,7.9274D-1
```

```
& , -5.8634D0,9.1089D1/
```

C..

C.. Convert T to Kelvin, P to bars

```
T = TIN + 273.16
```

```
P = PIN * 1.01325D0
```

C.. Get mean values equations 9-5.25 to 9-5.30

```
SM3 = 0.
```

```
EKM = 0.
```

```
MWM = 0.
```

```
DO 2 I = 1,NGAS
```

```
DO 1 J = 1,NGAS
```

C.. equations 9-5.32 TO 9-5.40

C.. kappa is 0 for these gases, mu also

```
IF(I.EQ.J)THEN
```

```
SIJ = .809*(VC(I)**(1.D0/3.D0))
```

```
EKIJ = TC(I)/1.2593D0
```

```
MIJ = MW(I)
```

```
ELSE
```

$$SIJ = .809D0 * \text{SQRT}((VC(I) ** (1.D0/3.D0)) * (VC(J) ** (1.D0/3.D0)))$$

$$EKIJ = \text{SQRT}(TC(I) * TC(J)) / 1.2593D0$$

$$MIJ = 2.D0 * MW(I) * MW(J) / (MW(I) + MW(J))$$

END IF

$$SM3 = SM3 + SIJ * SIJ * SIJ * Y(I) * Y(J)$$

$$EKM = EKM + Y(I) * Y(J) * EKIJ * SIJ * SIJ * SIJ$$

$$MWM = MWM + Y(I) * Y(J) * EKIJ * SIJ * SIJ * \text{SQRT}(MIJ)$$

1 CONTINUE

C.. rhom must be in mol/cm3 for use in calculating yy below

C.. subroutine returns in gm/cm3

2 CONTINUE

$$RHOM = \text{RHO}(Y, TIN, PIN)$$

$$EKM = EKM / SM3$$

$$TSM = T / EKM$$

$$MWM = MWM * MWM / (EKM * EKM * (SM3 ** (4.D0/3.D0)))$$

C.. equations 9-5.41 to 9-5.44 with omissions for $\mu = \kappa = \omega = 0$

$$TCM = 1.2593D0 * EKM$$

$$VCM = SM3 / (.809 * .809 * .809)$$

$$FCM = 1.D0$$

$$CVM = CP(Y, TIN) - R$$

$$ETA0 = \text{VISC}(Y, TIN, .01D0) * 1.D-7$$

C..low pressure viscosity must be in N-s/m2 rather than uP

C..

C.. Use these mean values in equations 10-5.5 to 10-5.6 and 10-6.6

C.. as recommended on page 539

$$ALPHA = (CVM / R) - 1.5D0$$

$$TR = T / TCM$$

$$BETA = .7862$$

$$Z = 2.D0 + 10.5D0 * TR * TR$$

C.. Upsilon equation 10-3.17

$$UPS = 1.D0 + ALPHA * ((.215D0 + .28288D0 * ALPHA - 1.061D0 * BETA + .26665D0 * Z) /$$

```

& (.6366D0+BETA*Z+1.061D0*ALPHA*BETA))
MPRIME=MWM/1000.D0
Q=3.586D-3*SQRT(TCM/MPRIME)/(VCM**(2.D0/3.D0))
DO 3 I=1,7
B(I)=A(I)
3 CONTINUE
YY=VCM*RHO(Y,TIN,PIN)/6.D0
G1=(1.D0-.5D0*YY)/((1.D0-YY)**3.D0)
G2=(B(1)/YY)*(1.D0-DEXP(-B(4)*YY))
G2=G2+B(2)*G1*DEXP(B(5)*YY)+B(3)*G1
G2=G2/((B(1)*B(4))+B(2)+B(3))
TK=31.2D0*ETA0*UPS*((1.D0/G2)+B(6)*YY)
TK=TK/MPRIME
TK=TK+Q*B(7)*YY*YY*G2*SQRT(TR)
RETURN
END

```

C..

```
REAL*8 FUNCTION VISC(Y,TIN,PIN)
```

C..

C.. Input is the vector of mol fractions of CO₂,H₂,H₂O,He,N₂,O₂ in the

C.. gas mixture, Y. Temperature, TIN, degrees C, pressure PIN, atmospheres.

C.. Output is the mixture viscosity in micro Poise.

C.. Formula from pages 388-490, chapter on viscosity and

C.. from constants in appendix A of Reid, Robert C, John M Prausnitz,

C.. Bruce E Poling; The properties of gases and liquids, 4th edition

C.. McGraw-Hill NY,NY ,1987.

C..

C.. TC, and PC for H₂ and He are changed as suggested by Gunn etal

C.. AIChE J 12,937(1966), in addition ad-hoc adjustments have been made to

C.. VC to make viscosity at low pressures match tables for these 2 gases

C.. omega is taken as zero for all gases

```

C..
    INCLUDE 'g2con.for'

C..
    DIMENSION A(10),E(10)

    DATA A/6.324D0,1.21D-3,5.283D0,6.623D0,19.745D0,-1.9D0,
&    24.275D0,.7972D0,-.2382D0,.06863D0/

C.. Convert T to Kelvin, P to bars
    T=TIN+273.16
    P=PIN*1.01325D0

C.. Get mean values equations 9-5.25 to 9-5.30
    SM3=0.
    EKM=0.
    MWM=0.
    DO 2 I=1,NGAS
    DO 1 J=1,NGAS

C.. equations 9-5.32 TO 9-5.40

C.. kappa is 0 for these gases, mu also
    IF(I.EQ.J)THEN
        SIJ=.809*(VC(I)**(1.D0/3.D0))

C..Ad hoc adjustments for He and H2
        IF(I.EQ.2)SIJ=SIJ/1.09D0
        IF(I.EQ.4)SIJ=SIJ/1.195D0
        EKIJ=TC(I)/1.2593D0
        MIJ=MW(I)
    ELSE
        SIJ=.809D0*SQRT((VC(I)**(1.D0/3.D0))*(VC(J)**(1.D0/3.D0)))

C..Ad hoc adjustments for He and H2
        IF((I.EQ.2).OR.(J.EQ.2))SIJ=SIJ/1.09D0
        IF((I.EQ.4).OR.(J.EQ.4))SIJ=SIJ/1.195D0

C..
    EKIJ=SQRT(TC(I)*TC(J))/1.2593D0

```

```

      MIJ=2.D0*MW(I)*MW(J)/(MW(I)+MW(J))

      END IF

      SM3=SM3+SIJ*SIJ*SIJ*Y(I)*Y(J)

      EKM=EKM+Y(I)*Y(J)*EKIJ*SIJ*SIJ*SIJ

      MWM=MWM+Y(I)*Y(J)*EKIJ*SIJ*SIJ*SQRT(MIJ)

1      CONTINUE

C.. rhom must be in mol/cm3 for use in calculating yy below

2      CONTINUE

      RHOM=RHO(Y,TIN,PIN)

      EKM=EKM/SM3

      TSM=T/EKM

      MWM=MWM*MWM/(EKM*EKM*(SM3**(4.D0/3.D0)))

C.. equations 9-5.41 to 9-5.44 with omissions for mu=kappa=0

      TCM=1.2593D0*EKM

      VCM=SM3/(.809*.809*.809)

      FCM=1.D0

C.. Use these mean values in equations 9-6.16 to 9-6.21 as recommended

C.. on page 432

      DO 3 I= 1,10

      E(I)=A(I)

C.. E(i) has more terms if kappa and mu are not 0

3      CONTINUE

      YY=RHOM*VCM/6.D0

      G1=(1.D0-.5D0*YY)/((1.D0-YY)**3.D0)

      G2=E(1)*(1.D0-DEXP(-E(4)*YY))/YY

      G2=G2+E(2)*G1*DEXP(E(5)*YY)

      G2=G2+E(3)*G1

      G2=G2/(E(1)*E(4)+E(2)+E(3))

      ETASS=E(7)*YY*YY*G2*DEXP(E(8)+(E(9)/TSM)+(E(10)/(TSM*TSM)))

      OMEGAV=1.16145D0*(TSM**(-.14874D0))+.52487*DEXP(-.77320*TSM)

      OMEGAV=OMEGAV+2.16178*DEXP(-2.43787D0*TSM)

```

```
ETAS=ETASS+((SQRT(TSM)*FCM*((1.D0/G2)+E(6)*YY))/OMEGAV)
```

```
ETA=ETAS*36.344D0*SQRT(MWM*TCM)/(VCM**{(2.D0/3.D0))
```

```
VISC=ETA
```

```
RETURN
```

```
END
```

```
C..
```

```
REAL*8 FUNCTION RHO(Y,TIN,PIN)
```

```
C..
```

```
INCLUDE 'g2con.for'
```

```
C..
```

```
C.. Input T, temperature degrees C, pressure in atmospheres,
```

```
C.. returns gas density in mol/cm3
```

```
C.. Formula for virial equations from page 37 of Reid, Robert C,
```

```
C.. John M Prausnitz,
```

```
C.. Bruce E Poling; The properties of gases and liquids, 4th edition
```

```
C.. McGraw-Hill NY,NY ,1987.
```

```
C.. Coefficients from CRC handbook of chemistry and physics 73rd edition
```

```
C.. 1992 taken from JH Dymond and EB Smithe, The virial coefficients of
```

```
C.. pure gases and mixtures, a critical compilation, Oxford U press,
```

```
C.. Oxford,1980
```

```
C..
```

```
DIMENSION A(5,NGAS)
```

```
DATA A/-127.D0,-288.D0,-118.D0,0.,0.,
```

```
& 15.4D0,-9.D0,-.2D0,0.,0.,
```

```
& -1158.D0,-5157.D0,-10301.D0,-10597.D0,-4415.D0,
```

```
& 12.D0,-1.D0,0.,0.,0.,
```

```
& -4.D0,-56.D0,-12.D0,0.,0.,
```

```
& -16.D0,-62.D0,-8.D0,-3.D0,0./
```

```
C..
```

```
T=TIN+273.16
```

```
P=1.01325*PIN
```

C..P in atmospheres, convert to bars

R = 83.144

C..R bar-cm³/(mol-K)

RHOM = 0.

T0 = (298.15/T) - 1.D0

DO 1 J = 1,NGAS

B = A(1,J) + T0*(A(2,J) + T0*(A(3,J)*T0*(A(4,J) + T0*A(5,J))))

Z = 1.D0 + (B*P/(R*T))

V0 = R*T*Z/P

RHOM = RHOM + (Y(J)/V0)

1 CONTINUE

RHO = RHOM

RETURN

END

C..

REAL*8 FUNCTION CP(Y,TIN)

C..

C.. Input is the vector of mol fractions of CO₂,H₂,H₂O,He,N₂,O₂ in the

C.. gas mixture, Y. Temperature, TIN, degrees C, PIN in atmospheres.

C.. Output is the mixture isobaric heat capacity in J/(mol-K),

C.. Formula and constants in appendix A of Reid, Robert C, John M Prausnitz,

C.. Bruce E Poling; The properties of gases and liquids, 4th edition

C.. McGraw-Hill NY,NY ,1987.

C..

INCLUDE 'g2con.for'

C..

DIMENSION CPVAPA(NGAS),CPVAPB(NGAS),CPVAPC(NGAS),CPVAPD(NGAS)

C.. DATA PARAMETER/CO₂,H₂,H₂O,HE,N₂,O₂/99-75-77-48-56-59

DATA CPVAPA/19.8D0,27.14D0,32.24D0,20.8D0,31.15D0,28.11D0 /

DATA CPVAPB/.07344D0,9.274D-3,1.924D-3,0.,-1.357D-2,-3.68D-6 /

DATA CPVAPC/-5.602D-5,-1.381D-5,1.055D-5,0.,2.68D-5,1.746D-5 /

DATA CPVAPD/1.715D-8,7.645D-9,-3.596D-9,0.,-1.168D-8,-1.065D-8 /

C.. Convert T to Kelvin, P to bars

P=PIN*1.01325

T=TIN+273.16

CPM=0.

DO 1 J=1,NGAS

CPJ=CPVAPA(J)+T*(CPVAPB(J)+T*(CPVAPC(J)+T*CPVAPD(J)))

CPM=CPM+Y(J)*CPJ

1 CONTINUE

CP=CPM

RETURN

END

C..

REAL*8 FUNCTION VPH2O(T,nP)

IMPLICIT REAL*8(A-H,O-Z)

C.. Input T, temperature degrees C, P in atmospheres

C.. returns vapor pressure of water

C.. in torr. Formula from appendix A of Reid, Robert C, John M Prausnitz,

C.. Bruce E Poling; The properties of gases and liquids, 4th edition

C.. McGraw-Hill NY,NY ,1987 verified by comparison with

C.. Handbook Chemistry and Physics,page D-109,49th edition,

C.. Robert C Weast(editor) Chemical Rubber Co., Cleveland,Ohio,1968

C.. Maximum error <.25%

TC=647.3

PC=221.2

VPA=-7.76451

VPB=1.45838

VPC=-2.77580

VPD=-1.23303

X=1.-((T+273.16)/TC)

X3=X*X*X

$$FX = VPA * X + VPB * (X ** 1.5) + X3 * (VPC + X3 * VPD)$$

$$FX = FX / (1.D0 - X)$$

$$PVP = PC * DEXP(FX)$$

C..PVP is in bars, convert to torr

$$VPH2O = PVP / .00133322368421$$

C..Correction for depth Glasstone, Samuel; Textbook of Physical Chemistry

C..2nd edition, fifth printing, 1946; D Van Nostrand Co Inc pp 446

$$TA = T + 273.16$$

$$PB = P * 1.01325$$

$$VW = 18.0686834$$

$$R = 83.144$$

C..R in bar-cm³/mol-K

$$CF = DEXP(VW * (PB - PVP) / (R * TA))$$

$$VPH2O = VPH2O * CF$$

RETURN

END

C..